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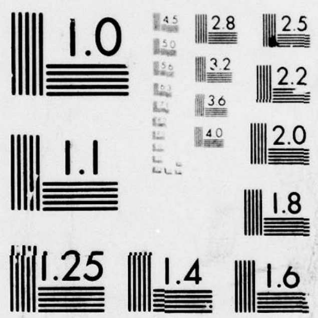

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JA-6A CIRCULATION CONTROL WING CONTRACTOR FLIGHT DEMONSTRATION

by

(10) Mr. R. W. Boyd

(11) 28 August 1979

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A Circulation Control Wing (CCW) Flight Demonstrator was designed and built by Grumman Aerospace Corporation (GAC) using a modified A-6A airplane. The design was a joint effort by David Taylor Naval Ship Research and Development Center (DTNSRDC) and GAC based on research originated by DTNSRDC. The airplane demonstrated significant STOL potential. Compared to the basic A-6A airplane, takeoff and landing roll distances were improved by 36% and 43%, respectively. Maximum C_L was increased by 80%. Some Handling Qualities problems are discussed. The CCW concept was shown to be a viable, simple, and powerful STOL tool for use in future designs.

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PREFACE

A contract was let in 1975 to Grumman Aerospace Corporation to study the feasibility of modifying an A-6A airplane to a Circulation Control Wing (CCW) configuration. A follow-on contract provided for the design, modification, and flight demonstration of the JA-6A CCW airplane. The Naval Air Test Center acted as Navy flight test consultant during the ensuing flight test evaluation. This memorandum summarizes the results of the evaluation.

APPROVED FOR RELEASE

J. G. WISSLER, RADM, USN
Commander, Naval Air Test Center

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INTRODUCTION

BACKGROUND

1. The Circulation Control Wing (CCW) concept, based on the well-known Coanda effect, involves converting the trailing edge of an airfoil into an enlarged rounded surface to which a jet sheet will adhere when blown tangentially from the upper surface. The blowing significantly alters the location of the aft stagnation point of the airfoil, providing more efficient airflow circulation. By increasing circulation of the airfoil, the blowing greatly enhances lift production and thereby decreases stall speeds and takeoff and landing distances. The CCW concept has been under development by the David Taylor Naval Ship Research and Development Center (DTNSRDC) since 1970, including 2 years of wind tunnel testing with a 12% scale A-6A CCW model achieving in the wind tunnel a 100% increase in maximum lift coefficient compared to the basic A-6A airplane. NAVAIRTESTCEN became involved in the A-6A CCW program in 1975 by assisting DTNSRDC personnel in preparing a test program for the proposed A-6A CCW. NAVAIRTESTCEN support was confined to a consultant role through the Naval Plant Representative Office requiring on-site witnessing of all significant flight test events at the GAC facility, Bethpage, New York.

PURPOSE

2. The purpose of this evaluation was to verify the aerodynamic performance of the CCW concept in a full scale tactical vehicle.

DESCRIPTION OF TEST AIRPLANE

3. The JA-6A CCW airplane, BuNo 151568, was a standard A-6A airplane with the following modifications:

a. Engine and bleed system modifications:

(1) Engine bleed system was enlarged to provide up to 10% of total compressor airflow to the CCW ducting.

(2) Bleed air ducts were added externally to provide air to the wings as shown in appendix A, figure 1.

(3) Control valves were located in bleed air ducts, as shown in appendix A, figure 1, two per engine to regulate the amount of air to the wings.

(4) A crossover duct between the two engine bleed air ducts supplied equal airflow to both wings under all conditions (appendix A, figure 1).

(5) A calibrated instrumented section of duct between the crossover duct and the wing duct allowed measurement of airflow to both wings (appendix A, figure 1).

b. Wing modifications:

(1) A rounded trailing edge doubled as a Coanda surface and a wing duct through which air was supplied to a slot on top of the wing as shown in appendix A, figures 1 and 2.

(2) A large wing fence was placed at the outboard end of the wing duct to control spanwise flow (appendix A, figure 2).

(3) The leading edge slat included an increased leading edge radius and an integrated Kruger flap on the wing fillet, shown in appendix A, figure 3. The air conditioner inlet was moved to the Kruger flap.

c. Control system modifications:

(1) A Reaction Control System (RCS) powered by bleed air tapped from the wing duct is shown in appendix A, figure 2. It was activated below 100 kt (51 m/s) whenever lateral stick position moved beyond 2 1/2 in. (75 mm). A two-position valve was used to modulate RCS thrust to counter adverse yaw.

(2) The horizontal stabilizer area was increased by 40% and cambered by addition of fairings on the leading and trailing edges as shown in appendix A, figure 4, to handle the anticipated nose-down pitching moments due to blowing.

(3) The A-6A Stability Augmentation System (SAS) was modified to improve low speed handling qualities, provide separate yaw, roll, or pitch axis selection, and improve reliability in the STOL regime. Modifications included gain changes in all axes, a lateral acceleration feedback in the yaw channel, faster servo-actuator response, isolation of the individual channels in the control box, and greater authority over the surfaces.

(4) The blowing was controlled by a slide switch on the throttle (replacing the speedbrake switch) and by the trigger switch on the stick grip. A Coanda pressure ratio (CPR) gauge was mounted on the pilot's panel (appendix A, figure 5).

(5) The rudder and elevator control linkages were locked into the full throw capability position.

d. Operational safety:

(1) The CG was held between the allowable 33.5% and 29% mean aerodynamic chard (MAC) by a valve between the mid and aft fuel tanks.

(2) The original Martin-Baker GRU-5 seats were replaced with GRU-7 seats with zero/zero capability.

(3) An emergency battery power system replaced the Ram Air Turbine (RAT) which does not function below 110 KIAS (57 m/s).

A detailed description of the JA-6A CCW airplane is given in reference 1.

SCOPE AND METHOD OF TESTS

4. The primary objective of this flight test effort was to define aerodynamic characteristics by performing a series of stabilized points. The airplane was stabilized at a selected blowing level, airspeed, angle-of-attack, and altitude for 1 min while all performance parameters were recorded via telemetry. From these data, smoothed values of C_L, C_D, and C_μ, etc. were computed. Handling qualities were evaluated throughout the flight envelope by performing elevator doublets, rudder doublets, steady heading sideslips, slow accelerations and decelerations, and shallow bank-to-bank turns. Takeoffs were performed with no blowing, partial blowing, and with preselected blowing turned on at airplane rotation for minimum distance. Landings were performed with no blowing and full blowing. All approaches used a 3 deg glideslope. Ground tests were conducted for checkout of bleed air control valves and for wing slot gap measurements. Wing slot gaps were measured with no blowing using a blade feeler gauge. With blowing selected, slot gaps were measured with special remotely operated tapered pins. These pins were moved into the slots while under pressure and were marked with a file and measured after shutdown with a micrometer.

1) Grumman Aerospace Corporation Report, Design of an A-6A Flight Demonstrator Aircraft Modified with a Circulation Control Wing, of 26 Jan 1978 (Limited Distribution).

RESULTS AND DISCUSSION

CIRCULATION CONTROL WING THEORY

Coanda Effect

5. A jet sheet blown tangentially over a cylindrical surface will adhere to the surface and will turn as shown in figure 1 (from reference 2). As long as the pressure-centrifugal force balance of equation (1) exists, the jet will turn and remain attached to the surface. By proper design, maximum turning angle can approach 180 deg. This principle is known as the Coanda effect.

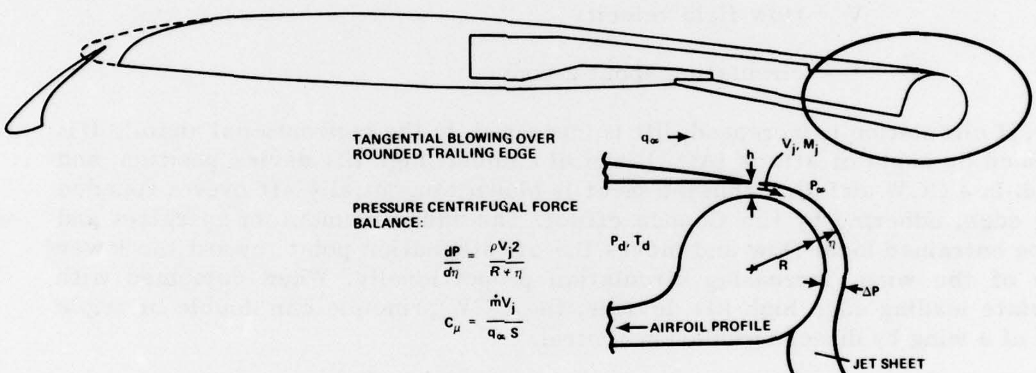


Figure 1
Basic Circulation Control Aerodynamics

6. The strength of the jet sheet is defined by the jet momentum, $\dot{m}Vj$ where $\dot{m}$ is mass flow and Vj is jet speed. Note the relationship between the jet momentum and thrust for a nozzle,

$$T = ma = \dot{m}Vj \tag{3}$$

so that $\dot{m}Vj$ is also a measure of the thrust contributed by the jet sheet at the slot. Of course, since the jet loses momentum by frictional and turning forces before it leaves the airframe, the actual thrust contribution is much lower. The nondimensional parameter used for the CCW blowing measurement is defined as:

$$C_\mu = \frac{\dot{m}Vj}{qS} \tag{2}$$

2) Englar, R.J., Trobaugh, L.A., and Hemmerly, R.A., STOL Potential of the Circulation Control Wing for High Performance Aircraft, AIAA Paper 77-578, Palo Alto, California, June 6-8, 1977.

This parameter shares equal importance with C_L and C_D for a CCW airplane. Handling qualites and performance characteristics are strongly influenced by C_μ, as will be discussed later.

Circulation Theory

7. In conventional aerodynamics, it can be shown (reference 3) that:

$$L = \rho V \Gamma \tag{4}$$

where L = lift

ρ = density of fluid

V = flow field velocity

Γ = circulation about a bcdy.

Clearly, if circulation is increased, lift is increased. In the conventional airfoil, Γ is determined by angle of attack (AOA), airfoil camber, high lift device position, and airspeed. In a CCW airfoil, a thin jet sheet is blown tangentially aft over a rounded trailing edge, adhering by the Coanda effect. The added momentum energizes and turns the entrained local flow and moves the aft stagnation point toward the lower surface of the wing, increasing circulation proportionally. When combined with appropriate leading edge high lift devices, the CCW principle can double or triple the lift of a wing by direct circulation control.

8. A side benefit for STOL applications is the large induced drag increment associated with the augmented lift, providing improved glide path control during STOL approaches. CCW designs also exhibit larger stabilizing longitudinal moment characteristics which vary as a function of blowing. Ideally, a CCW airplane design should include a horizontal tail located where trim changes due to these larger moments are minimized. Lateral and directional controls should have sufficient authority and feel to perform closely controlled tasks at minimum airspeeds.

AERODYNAMIC PERFORMANCE

9. The airplane aerodynamic performance was measured by recording engine parameters, airmass information, and gross weight over a 1 min time span while the airplane was stabilized. Net thrust was calculated by a proven A-6A computer routine while excess thrust was calculated from airspeed and altitude time histories. Power-off lift and drag were computed using these values corrrected for power effects and spoiler deflection. Indirect power effects such as

3) Kuethe, A.M. and Schetzer, J.D., Foundations of Aerodynamics, John Wiley & Sons, Inc., 1959.

exhaust-induced flow were not included. Data are presented in appendix A, figure 6, as a relation of C_L, AOA, and C_μ. The highest C_L achieved was 3.6 (corrected for spoiler deflection) at a C_μ of 0.212 and an AOA of 17 deg. Test data values of C_L are very close to the wind tunnel estimates for each value of AOA and C_μ tested. At the higher values of C_μ, large amounts of lateral stick were required to trim the airplane resulting in corrections on the order of 0.26 in C_L. Time and money did not allow a large test matrix to identify all the possible corrections to C_L, but the close agreement with wind tunnel estimates raises the confidence level in the data presented. Test values of C_D at lower C_μ did not agree with wind tunnel data but agreement did occur at higher C_μ values.

FLYING QUALITIES

Longitudinal Flying Qualities

10. Handling qualities of the JA-6A CCW airplane were of secondary emphasis in the test program; however, several significant areas were of interest. Longitudinal flying qualities were evaluated throughout the flight envelope. With no blowing, the airplane had neutral static stability with some instability in the 18 deg to 26 deg AOA region. Above 26 deg AOA, the airplane became slightly statically stable. With increasing amounts of blowing, the airplane became slightly more statically stable up to 17 deg AOA when it again became statically unstable. The airplane required 0 deg trim with no blowing and 5.5 deg TEU (Trailing Edge Up) trim with full blowing. Wind tunnel estimates for trim showed an expected 21 deg TEU with full blowing. The wind tunnel estimates did not include the effects of exhaust impingement on the horizontal stabilizer, which were apparently significant. The short period oscillations were essentially deadbeat throughout the envelope with response becoming more sluggish with decreasing airspeed. Maneuvering longitudinal stability was qualitatively evaluated and was acceptable throughout the envelope.

11. Blowing could not always be held constant. It was often accidentally decreased by activating the tip jets or by drift in the flow control valves. Since AOA stability was neutral, a steady pitch rate would result and would require positive pilot inputs to stop. On one occasion, the airplane smoothly pitched from 18 deg to 26 deg AOA in only 5 sec of inattention following tip jet activation. Since AOA stability was very poor, the airplane required constant attention to maintain trim AOA. Any future application of the CCW concept should include a more sophisticated control system with integrated SAS and automatic blowing control to provide apparent AOA stability.

Lateral-Directional Flying Qualities

12. Wind tunnel predictions of lateral-directional flying qualities were mostly accurate with some exceptions. The airplane showed decreasing directional stability with decreasing airspeed, as predicted, with the airplane becoming neutrally stable directionally below 100 kt (51 m/s). With yaw SAS engaged, the directional stability remained slightly positive down to minimum flying speed (68 kt (35 m/s)). The dutch roll mode showed mostly yaw oscillations with roll-to-yaw ratios of less than one. The exact value of roll-to-yaw ratio was masked by the

requirement to manually stabilize roll attitude. Pilot comments indicated dihedral effect ($C_{\ell\beta}$) seemed much lower than predicted, simplifying the task of stabilizing the airplane.

13. Lateral lift imbalances caused the primary handling qualities deficiencies. With no blowing, the airplane required half right wing down trim. With increasing blowing, the trim required traversed to full left wing down plus additional left stick force. As blowing was further increased, a region was reached (mil power full blowing, 5,000 ft (1 525 m)) where the airplane required 0 deg lateral trim at 10 deg AOA, transitioning to more than full right wing down trim at 12 deg AOA, and to more than full left wing down trim at 16 deg AOA. If the airplane were trimmed between 12 deg and 16 deg AOA, the airplane would alternate between right wing heavy and left wing heavy, requiring the pilot to change lateral stick force and rudder to balance the airplane. At 18 deg AOA, a discontinuity occurred in lateral control effectiveness which caused sudden wing drops in the direction of applied aileron. The aerodynamic mechanism appeared to be sudden separation of the flow on the Coanda trailing edge. Since this "trip point" appeared to be at approximately 2 in. (50 mm) of lateral stick travel and the stick required to trim was greater than 2 in. (50 mm), a trimmed point could not be obtained at 18 deg AOA.

TAKEOFFS, APPROACHES, WAVE-OFFS, AND LANDINGS

14. Takeoffs were performed with various amounts of blowing up to 80% of full blowing. In all cases, the horizontal stabilator effectiveness was sufficient to rotate the airplane at 55 KIAS (28 m/s) but the airplane would not accelerate in a nose high attitude. The best technique was to set trim for flyaway and let the airplane fly off with slight back pressure on the stick. Optimum takeoffs were obtained by: (1) setting blowing during ground run up prior to takeoff; (2) pulling the blowing circuit breaker to shut off the bleed regulator; (3) accelerating to an estimated rotation speed; and (4) pushing in the circuit breaker to achieve instantaneous blowing as the regulator popped open. Ground rolls of 700 ft (215 m) at a gross weight of 34,500 lb (15 650 kg) with light winds were achieved with 60% blowing using this technique, a 36% reduction from the basic A-6A airplane.

15. Approaches were flown using maximum available blowing but power setting was approximately 88% RPM, reducing the amount of blowing available. Approach speeds were approximately 40 kt (20 m/s) less than in the standard A-6A airplane. The airplane was trimmable about all axes in the approaches. In fact, approach AOA was defined in terms of lateral trimmability. The region between 12 deg and 16 deg AOA, where there was a drastic trim change with a small airspeed change, was undesirable. The region between 16 deg and 18 deg AOA and the region between 9 deg and 12 deg AOA, which were relatively stable regions, were used for actual approaches. Since approaches were conducted at partial power and, hence, lower blowing values, the lateral imbalance was less severe during the actual approaches. Gust sensitivity was very high, however, and, on several occasions, the lateral control discontinuity was perturbed trying to counter a gust. Gust sensitivity is a problem with many STOL concepts because of the magnitude of the gust velocities relative to the airplane velocity. Because of the lateral control discontinuity on this airplane, gusty conditions were even more restrictive. A more suitable lateral control, such as an augmented aileron or reaction control system, is needed in future applications of the CCW concept.

16. Wave-offs were performed from 200 ft (60 m) and consistently showed no altitude loss. The airplane did not rotate, but the additional blowing created by adding power for wave-off simply added a lift increment which arrested the sink rate. The pilot simply added power and held fixed control positions.

17. Landings were done with no blowing and with maximum available blowing. Twenty-two maximum blowing landings were accomplished during the program. The minimum stopping distance was 1,075 ft (325 m) with light winds at 33,400 lb (15 150 kg), a 54% reduction from the basic A-6A airplane. Given more time to develop an optimum technique, ground roll distances could be reduced. If the CCW concept were combined with reverse thrust, the landing roll would be further reduced.

EVALUATION OF OVERALL DESIGN

Horizontal Stabilizer

18. The horizontal stabilizer was enlarged and cambered to counter a predicted pitching moment which did not appear in full scale testing. As stated previously, the predicted tail incidence with maximum blowing differed by 16 deg from the actual values. The difference was attributed to engine exhaust induced flow over the wing producing increased downwash at the horizontal tail. This design oversight manifested itself in reduced static stability, bothersome pitch control sensitivity, limited nose down pitching moments, and flow separation on the horizontal stabilizer upper surface. Accidental benefits of this design oversight include milder pitch trim changes with blowing changes, milder recoveries from sudden blowing failure, and milder wave-off trim changes than predicted.

Bleed Air Control System

19. The bleed air control system was another design problem. Ideally, the four valves would be balanced and would operate together with the two closest to the engine (pressure regulators) providing a regulated pressure downstream and the next two (flow control valves) providing selected amounts of air to the Coanda ducts. In actuality, however, the pressure regulators were handicapped by the location of the sensors for the valve control feedback loop. They frequently provided excessive pressure error downstream, limiting the amount of blowing available. This problem was skirted by changing the procedure to open the valves fully at reduced engine power and then slowly adding power to maximum. The flow control valves were gear driven and required 3 to 4 sec to open fully. At intermediate valve positions, the valve was held by gear train friction alone. Vibration and pressure caused the valves to drift closed. This problem was rectified by changing the gear ratio by a factor of three.

20. The overall valve system, after correction, was still inadequate. Coanda pressure was a function of engine power setting with valves open fully. A more automatic control of Coanda pressure is required in future CCW applications to eliminate trim changes due to power changes.

Coanda Duct and Slot Gap

21. The Coanda duct and slot were designed so that they were flexible under pressure. As pressure in the duct increased, both the upper plate and the duct expanded, although not uniformly. The resultant slot gap measurements are shown in appendix A, figure 7. Note that they are asymmetric. The lateral trim changes discussed in paragraph 15 were attributed to this uneven distribution since local lift will vary with local slot gap size. Future CCW applications should require a more tightly controlled slot gap to eliminate lift asymmetry.

Control System

22. The combination of spoiler lateral control and CCW was not entirely successful, as previously discussed, and should not be attempted again. More work needs to be done with lateral controls, with augmented ailerons, differential blowing, or reaction controls being the most likely candidates. At the low airspeeds of a STOL airplane such as the JA-6A CCW, unaugmented aerodynamic controls are simply not powerful enough to balance the augmented lift. Directional control suffers the same penalty although it is feasible to design a larger vertical tail to accommodate the lower airspeeds. Longitudinal control may also need some augmentation in future designs to be compatible with both the high and low speed regimes.

Stability Augmentation System

23. Because of the brevity of the test program, SAS gains were based solely on wind tunnel estimates of stability derivatives and were not altered during the program. All three SAS channels worked as designed throughout the test program, although maneuvering the airplane at low speeds quite often saturated the yaw channel. For the approach condition, the SAS was quite active but was unable to eliminate sideslip excursions and could not stabilize AOA. Since the test airplane had a relatively small usable airspeed range with full blowing, airspeed excursions could not be tolerated. The pilot was heavily taxed by the close control of airspeed, AOA, roll, sideslip, and glide path. A future CCW concept must provide more stability about all axes and should incorporate automatic blowing and power control during final approach. The pilot could then concentrate on the actual approach and landing.

PERFORMANCE SUMMARY

24. The JA-6A CCW airplane successfully demonstrated a 42 kt (21 m/s) (36%) reduction in approach speed, a 1,320 ft (407 m) (54%) reduction in landing ground roll, a 635 ft (190 m) (42%) reduction in takeoff ground roll, and a C_L gain of 1.5 (71%) compared to the standard A-6A airplane. Although the JA-6A CCW airplane suffered major handling qualities problems, the data gathered will help to confirm the viability of the CCW concept and provide full scale "lessons learned" for future application. The problems encountered can be solved by proper design. The CCW concept should be considered for future STOL tactical airplane designs.

CONCLUSIONS AND RECOMMENDATIONS

25. Test values of C_D at lower C_μ did not agree with wind tunnel data but agreement did occur at higher C_μ values (paragraph 9).

26. Longitudinal static stability was essentially neutral becoming slightly positive with increasing blowing (paragraph 10).

27. Dutch roll damping was slightly positive at minimum airspeed with yaw Stability Augmentation System engaged (paragraph 12).

28. Lateral lift imbalances caused various handling qualities deficiencies (paragraph 13).

29. Incompatibility of the spoiler lateral control and the Circulation Control Wing (CCW) at high blowing caused sudden wing drops (paragraph 13).

30. A reduction of 42% in takeoff distance, 54% in landing distance, and 36% in approach speed was demonstrated (paragraphs 14, 15, 17, and 24).

31. The horizontal stabilizer effectiveness was much higher than predicted (paragraph 18).

32. A more automatic control of Coanda pressure is required in future CCW applications to eliminate trim changes due to power changes (paragraph 20).

33. The CCW concept should be considered for future STOL tactical airplane designs (paragraph 24).

FIGURES

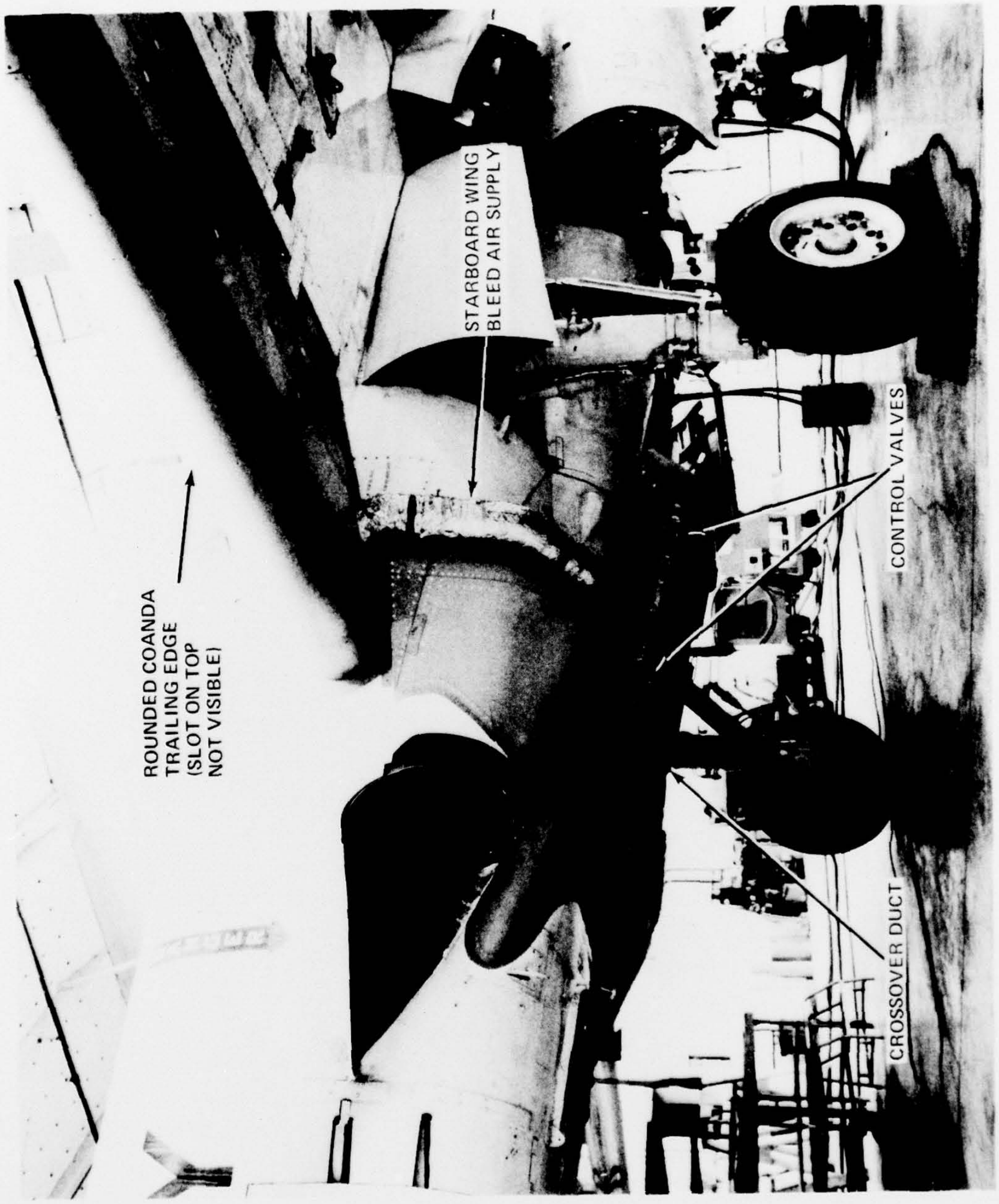


Figure 1
Rear View of Wing Root Area

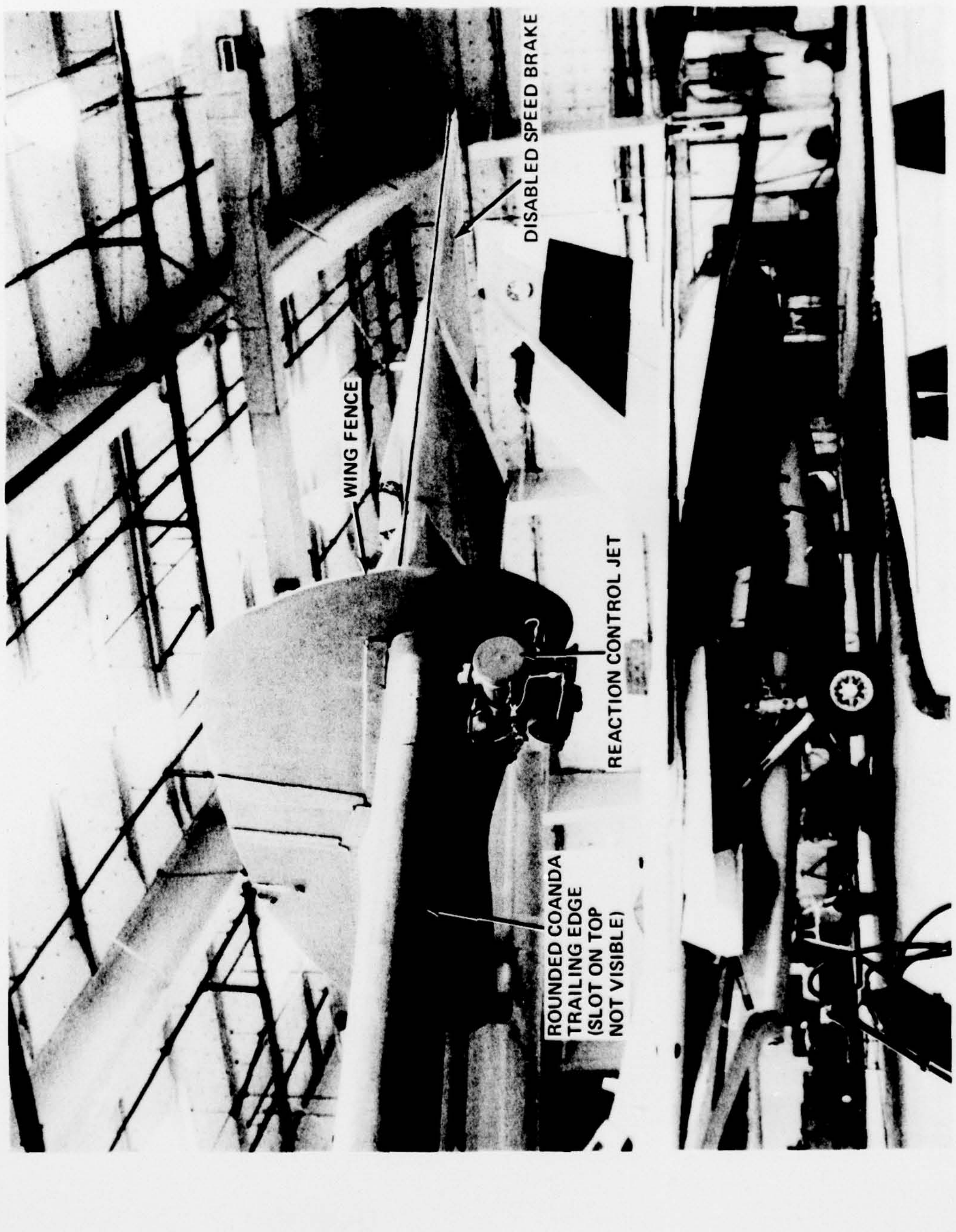


Figure 2
Rear View of Wing Tip Area

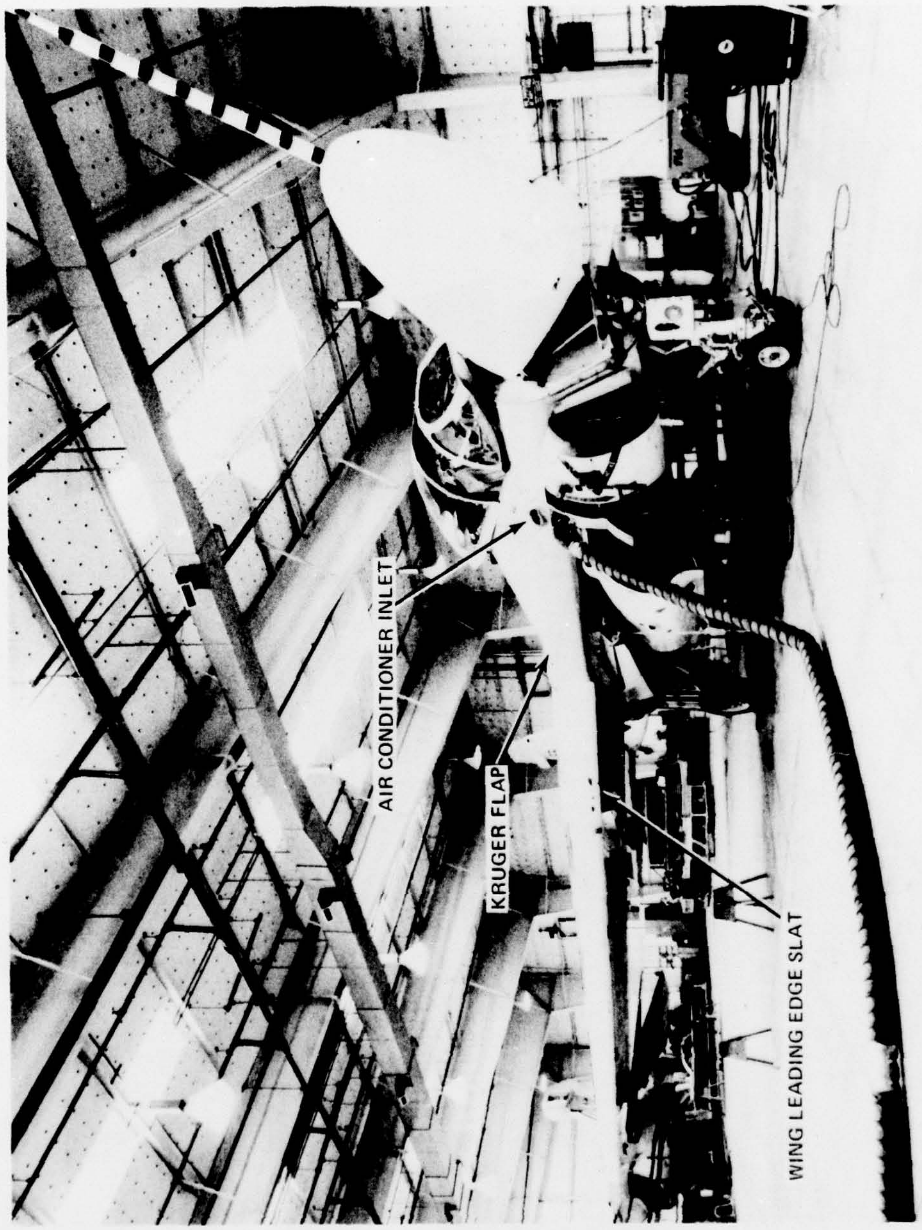


Figure 3
Front 3/4 View of Test Airplane

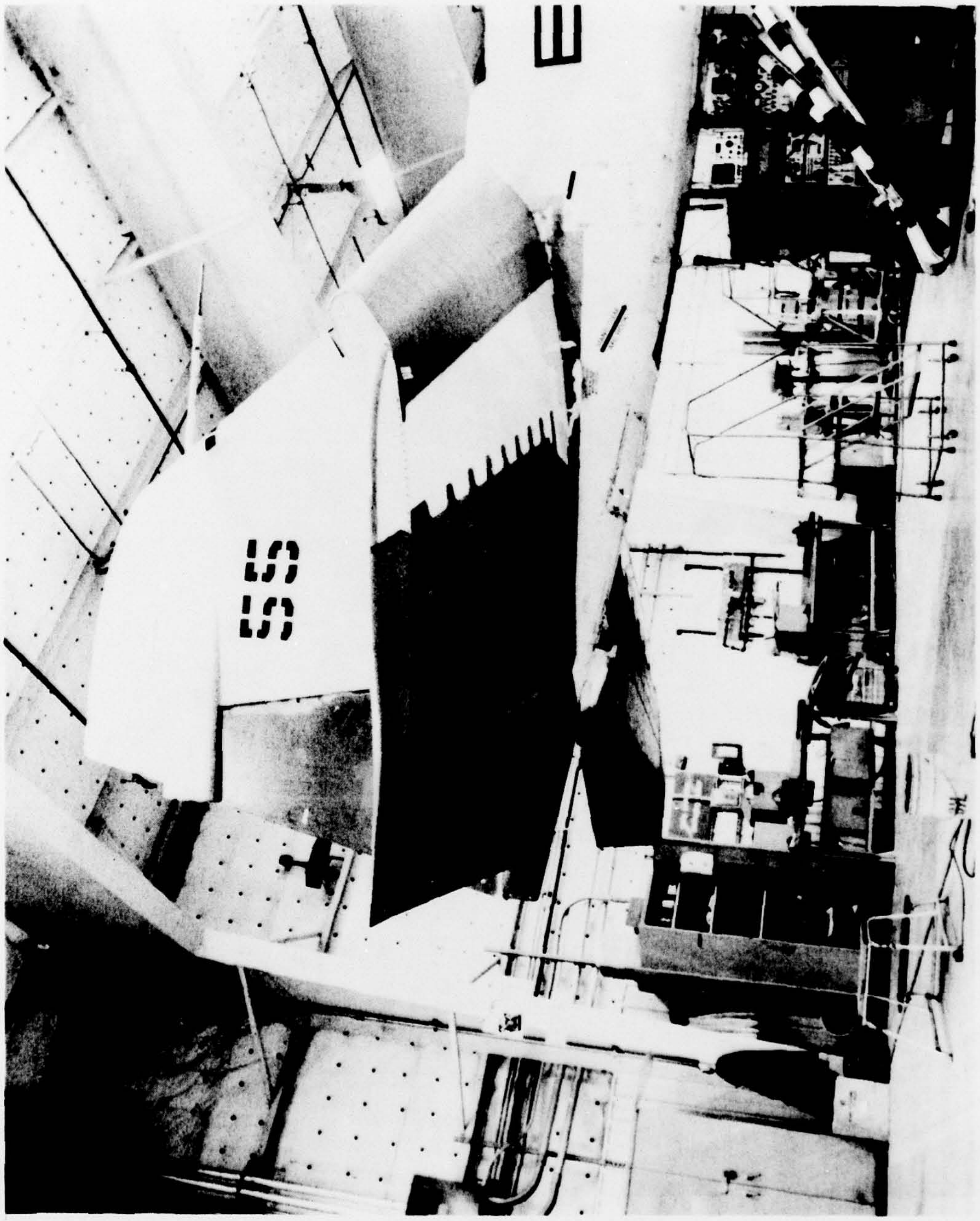


Figure 4
Side View of Tail Area

Figure 5
View of Pilot's Instrument Panel

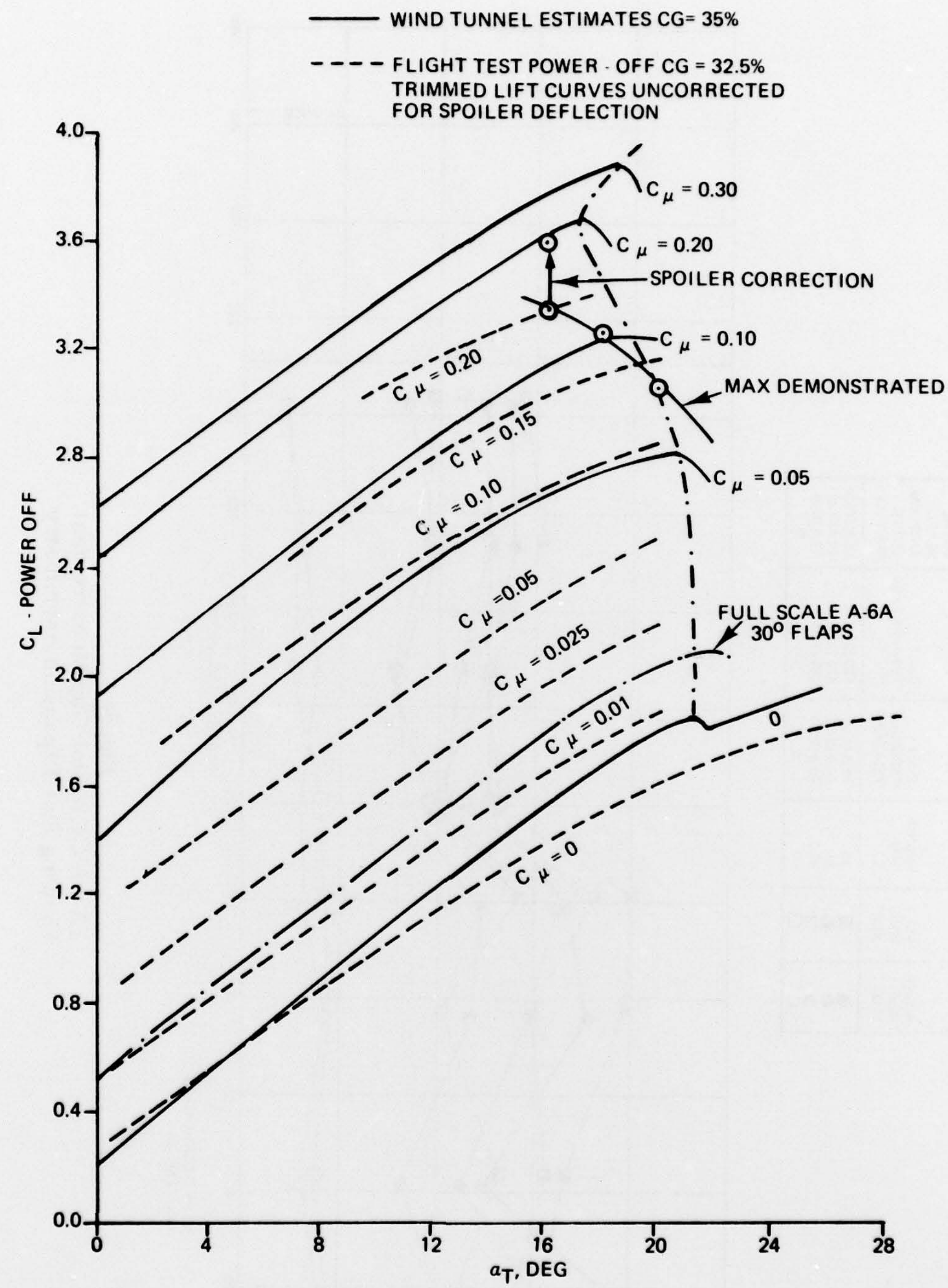
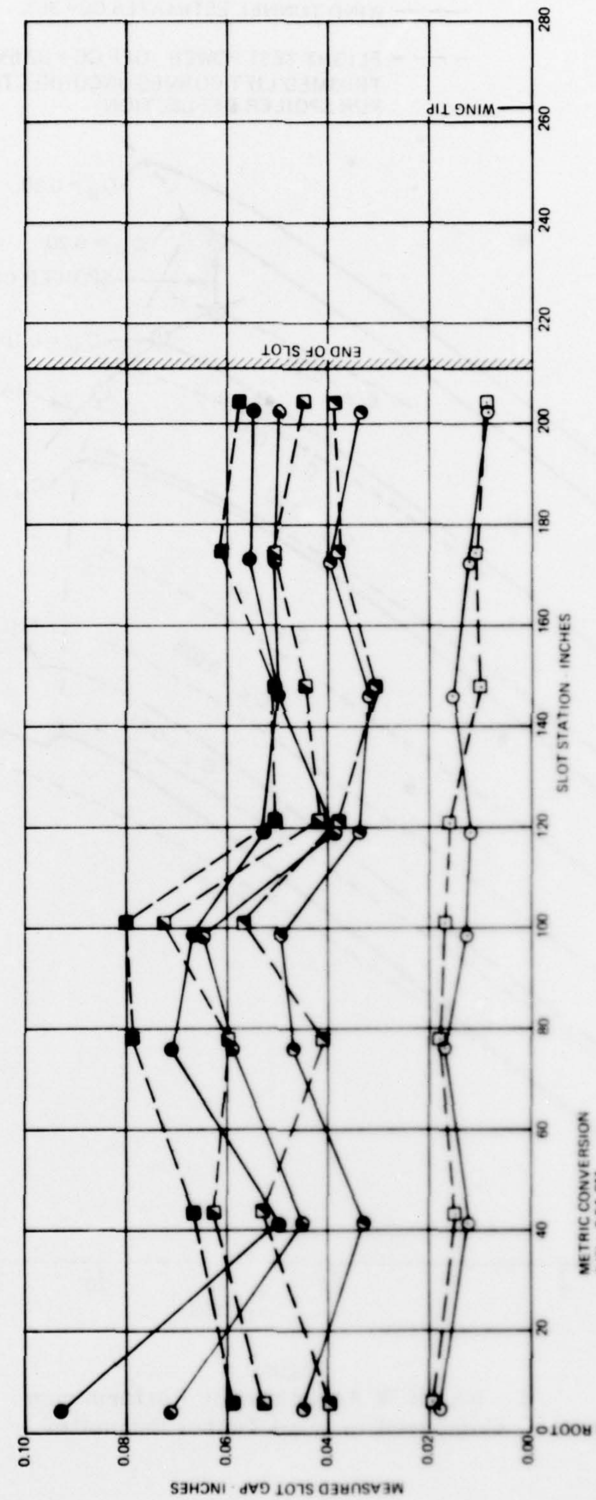


Figure 6
JA-6A/CCW Aerodynamic Performance
Compared to Wind Tunnel Estimates



RIGHT WING SLOT	LEFT WING SLOT	ENGINE RPM %	DUCT PRESSURE PSIA (KPa)	DUCT TEMPERATURE °F (°C)	TOTAL BLEED AIRFLOW LB/SEC (KG/SEC)
●	■	90	49.0 (338)	530 (277)	25.3 (11.5)
◕	◪	81	40.2 (277)	423 (217)	16.4 (7.4)
◑	◩	69.5	30.3 (208)	285 (140)	11.4 (5.2)
○	□	0	0	0	0

Figure 7
JA-6A CCW Slot Gap Measurement
Showing Slot Expansion Asymmetry

GLOSSARY OF TERMS

AOA	Angle of Attack
C_D	Drag Coefficient
C_L	Lift Coefficient
CCW	Circulation Control Wing
CPR	Coanda Pressure Ratio
C_μ	Momentum Coefficient
DTNSRDC	David Taylor Naval Ship Research and Development Center
GAC	Grumman Aerospace Corporation
L	Lift
$\dot{m}$	Jet Sheet Mass Flow
MAC	Mean Aerodynamic Chord
P_∞	Ambient Pressure
q_∞	Free Stream Dynamic Pressure
R	Coanda Surface Radius
S	Wing Area
SAS	Stability Augmentation System
STOL	Short Takeoff and Landing
TEU	Trailing Edge Up
V_j	Jet Sheet Velocity
V	Free Stream Velocity
Γ	Circulation
ρ_∞	Ambient Density
η	Jet Sheet Thickness

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